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ScienceDirect
Procedia CIRP 26 (2015) 305 – 310
www.elsevier.com/locate/procedia

12th Global Conference on Sustainable Manufacturing

A Lean Based Overview on Sustainability of Printed Circuit Board production assembly

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Abstract

With increasing the sustainability awareness, the goods that ends up with generating hazardous waste in dumps and landfills, are more discussed environmentally, socially, and economically. Printed Circuit Boards (PCBs), which form the basis of the high quality electronics product, are complicated to be produced due to the diversity of materials and components, and technologically waste of hazardous disposal due to the difficulty of a concrete recycling process. Thus, a sustainable life cycle of printed circuit boards requires a definite highlight of the material selection legislation, environmental burdens of the manufacturing process, and disposing and recycling process.
This article presents an overview on sustainability issues with Lean paradigm perspective in PCB assembly and resource consumption showing their structure and materials, legislation issues on material and production, and the alternative solutions for the recent green innovations and production of PCBs.

Peer-review under responsibility of Assembly Technology and Factory Management/Technische Universität Berlin.

Keywords: Printed circuit boards (PCBs) assembly, sustainable manufacturing, environmental problem

1. Introduction

The rising environmental awareness as well as worldwide increasing prices for natural resources imposes higher pressure on the products manufacturers. Especially for the complex products that end up with technological waste in dumps and recycling, it is more crucial to consider the alternatives for the material, design, manufacturing process, and disposal process in a way that there is no harm to the environment.

PCBs are compound of complex composition of hazardous materials [1], and, therefore, a rather complex product for recycling. In general, PCBs mounted with components consist of approximately 40 % of metals, 30 % of plastics, and 30 % ceramic [2]. For waste PCB without the mounting of electronic components, material composition comprises about 28 wt% of metal (mainly copper) and 72 wt% of non-metallic materials [3]. Though, the materials used in PCBs are hazardous and expensive, but the main cost is in the recycling and disposing process at the end of life cycle. In the separation process of the electronic components, it is necessary to remove them from the solder, which is a complex process, and it often makes the components unusable because of the temperature applied [4].

A possible cost reduction in electronics manufacturing industry can be achieved by reducing the energy demand of the manufacturing process as well as material used to produce the PCB product. A detailed study has already been done on recycling of PCBs as well as in terms of life cycle assessment for PCBs and PCB using products [5], but fewer studies for the energy consumption aspects in the PCB manufacturing [6].

This article presents an overview on sustainability issues with Lean paradigm perspective in PCB assembly and resource consumption showing their structure and materials, legislation issues on material and production, and the alternative solutions for the recent green innovations and production of PCBs.

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doi:10.1016/j.procir.2014.07.059

2. Electronics manufacturing services (EMS)

EMS came into being as the industry moved beyond printed circuit board (PCB) assembly services. As reported by Nakahara [7], printed circuit boards can be classified in many different ways according to their various attributes; for instance, single-sided boards, double-sided boards, multi-layer boards, and rigid and flexible boards. The IPC-2222 [8] provides design information for different types of boards. To connect the components on the circuit board, there are four methods [9]:

- Reflow soldering in surface mount technology (SMT).
- Wave-type soldering in Through Hole-Technology (THT).
- Interconnection pressure; a contact method with less solder that relies on mechanical strength to force the interconnectedness of the elements together.
- Press-fit; another mechanical method without solder.

The first two methods are the most conventional approaches in which the solder alloys are used as interconnection material to connect the components on the board.

3. Beyond lean manufacturing in electronics manufacturing services (EMS)

In the EMS sector, lean manufacturing model is a relatively recent advance. There are some case studies that have reported the investigation of value-added analysis and the process improvements using lean manufacturing concept [10, 11]. These studies mainly are investigating how to transform an electronics manufacturing process from a traditional batch-and-queue circuit board assembly process to a continuous flow manufacturing process. The main issue to solve using lean manufacturing methods is reducing work in process (WIP) inventory that is accumulating before the workstation, and too many pieces of WIP that require rework to correct defects from upstream production. Beyond this fact, the technology producers are innovating to convert the discontinuous processes to a continuous process for component placement using double line production, or the bottleneck before the soldering oven by using batch production methods and optimized temperature profile.

Kanban were adopted in an electronics manufacturing in UK to implement the just-in-time (JIT) concept and control the pull system which delivers dramatic reductions in lead times and inventory [12]. ASM Electronics Assembly Systems GmbH in Munich presented “Siplace SX”, the world’s first placement machine designed entirely for build-to-order processes, in order to adjust the production just-in-time according to the demand [13]. Single minute exchange of die (SMED) method is used in a surface mount technology (SMT) in the process of change line to separating the internal time and external time, reducing internal time and shortening external time. The process of change line has been cut down to 5min from 20min, and the capacity of production ascends 20 % [14]. Value stream mapping (VSM) method is used to prioritize sources of deadly wastes as listed by Womack and Jones [15]. In a value stream mapping investigation, the lean model reduced WIP from $1.9 million to $0.38 million and cut the manufacturing cycle time from 18 days to 3 days. Quality yields increased from 83.9 % to 99.7 % [11]. The application of lean concept is not only restricted to improve the production planning process but also to improve the resource consumption and increase the sustainability degree of electronics manufacturing industries. The U.S. Environmental Protection Agency (EPA) has given a recommendation to enhance the widely known lean process data by process specific energy use data [17], and Erlach and Westkämper introduced a rather more detailed assessment of resource flow and proposed a formulation for the energy intensity (EI) calculation [11].

The above explained studies however traditionally were seen as solutions for time and cost reduction but inherently are targeting different forms of wastes and incorporate strong environmental impacts in EMS.

4. Lean and Green paradigm in PCB assembly

Studies underline a strong coherence and interdependencies between lean and green activities and both are sharing similar basics with eliminating waste as the major perspective. Therefore, policy makers such as U.S. environmental protection agency (EPA) propose the implementation of lean methods as a promising way to reduce the wastes and improve the environmental results [18]. The deadly wastes which are defined by Womack and Jones [15] are also adopted for environmental impacts in PCBs assembly:

1. Raw material and energy consumed to make unnecessary products.
2. Work in process (WIP) inventory. WIP inventory causes the stoppage of downstream stations; machines are still using electrical power while not producing.
3. More space and energy required to store WIP movement and transportation.
4. Defective products consuming energy and material, and efforts for recycling.
5. Unnecessary processing increases waste, energy use, and emissions. It is required to minimize the unnecessary resource consumption.
6. Wasted energy from electric power, heating, cooling during the process down time.

The primary wastes in PCB assembly are solder paste waste, solder dross, solvents, volatile organic compounds from soldering operations, and waste water. Energy is consumed in thermal and mechanical processes. Process yield can also be an important factor impacting waste generation, since alternative processes have different yields for scrap, rework, and long term reliability. Figure 1, highlights the resource flow map and the wastes stream. Worhach et al. [19] also defined models in a case study for the unit-level and batch processes and the waste stream in PCB assembly manufacturing.

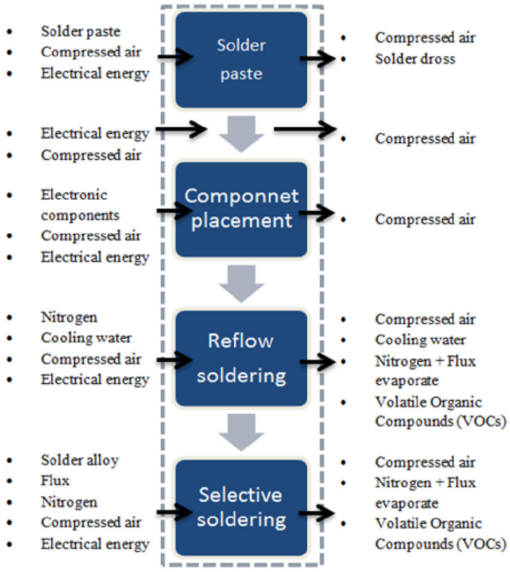

Fig. 1. The resource flow map in PCB assembly.

5. Sustainability aspects of PCB assembly manufacturing

5.1. waste electrical and electronic equipment (WEEE)

The United Nations Environment Program [20] points out that the amount of electrical and electronic equipment (EEE) placed on the market every year is increasing both in industrialized countries. On the other hand, the available data on generation of waste electrical and electronic equipment (WEEE) is poor and insufficient. Through estimation techniques that extended known data to regional-global coverage, the UNEP report predicted an increase from 200 % to 400 % in the generation of WEEE in developing countries from 2010 to 2020 [20].

This program is aggravated by the peculiarities of WEEE: it contains more than a thousand different substances [21], many of which are high-valued and/or highly toxic, and thus are both great sources of precious materials and waste disposal related issues [22]. It has been estimated that, prior to EU enlargement, each citizen of the 15 member states generated 23 kg of electrical/electronic waste per annum [23]. While Hansen and Leipprand identified that the quantity of WEEE generated annually increases by a rate of 16% – 28% per annum [24]. As PCBs are constituents of most electrical equipment it is natural to assume that large volumes of boards are being disposed in landfill sites. PCBs account for about 6 % of the total weight of WEEE. Indeed UK government bodies found that during 2002 over 6500 tons of manufactured PCBs from products such as computers are discarded each year [25]. This is a substantial quantity of waste entering landfills and the European Commission intends to address this mounting problem through the introduction of the WEEE [26] and restriction on hazardous substances (RoHS) [27] directives.

5.2. Halogen Free and Brominated Flame

Retardants recent concerns over use of brominated flame retardants (BFRs) in PCB assembly industry have increased the interest in halogen-free electronics. However, BFRs are not the only source of halogens in PCB. Most PCB resins are epoxies and epoxy resins contain measurable levels of chlorine. Additional halogens are added to PCB laminates through glass sizes, wetting agents, curing agents and resin accelerators. The International Electrochemical Commission (IEC) defines halogen-free based on chlorine and bromine levels. The most commonly used flame retardants in electronics are Tetrabromobisphenol-A (TBBPA) and Deca-Brominated Diphenyl Ether (DecaBDE). There are no bans or restrictions on the use of TBBPA or DecaBDE in EEE. However, other forms of BFRs are banned in the U.S. and Europe [27, 28].

5.3. Lead-free solder

Solder alloy is the material to connect the electrical components to the circuit board. The lead-based solders (63Sn37Pb solder) are the classical connecting material and are valid for any type of solder. It has a relatively low melting point (183 °C), good wettability, good mechanical, high conductivity properties, and low cost [29]. Although, the lead-based solders have a lot of advantages which is reducing the cost of the final product, legislations to prevent using these material promote new area of technology and process in PCB assembly manufacturing. The main impact of the use of lead-free solder is that the melting temperatures of the new substitute alloys are much higher than the classical solder alloys. For instance, a typical lead-free alloy, such as 96.5Sn/3.5Ag, melts at 221 °C. Since the melting temperatures (higher demand of energy consumption) of the new substitute alloys are higher, and they offer a lower wetting of metal surfaces, and therefore, they are more expensive [4].

5.4. Resource and cost efficiency

The resource consumption reduction is decreasing the final cost of the product while it is increasing the product sustainability. By the increase of the price for the scarce materials used in PCBs, it is needed to promote new strategies to overcome the restrictions. Mitigation of the material consumption, recovery and recycling of the scraps, however are important, but beforehand, a sustainable design and structure of PCB product in the very beginning phase of the life cycle prevent the material usage waste. Sandborn et al. studied the specific economic analysis of a PCB assembly and reported the following advancements [30]:

1) Increased circuit density through saving space on the substrate;
2) Decreased product weight;
3) Improved electrical properties through additional termination and filtering opportunities and shortening electrical connections;

4) Cost reduction through increasing manufacturing automation;
5) Increased product quality through the elimination of incorrectly attached devices;
6) Improved reliability through the elimination of solder joints.

All the equipment along the production line runs on electrical power. The pneumatic are supplied by compressed air and the soldering processes often are carried out in inert environment, for which industrial grade Nitrogen is used in the soldering oven. Water and cooling fans are used to remove heat from the reflow soldering furnace within its cooling zones. To analyze the resources consumption to produce the PCBs, the materials have been studied and the best practices for energy conservation in green board production are reported [31]; however the energy that is used in the assembly process is still in question. Especially, even when the soldering oven is realized as energy intensive process in PCB assembly, there is no approach to realize the specific energy consumption in this process. The Institute for Factory Automation and Production Systems (FAPS) as part of the Green Factory Bavaria project is working on this topic to realize the minimum energy consumption per each process in PCB assembly process. Also, the SurfEnergy project is providing a structured pathway to energy efficiency, with guidance on setting up an energy management system, energy auditing requirements, measure lists, tools for checking energy efficiency and investment advice [32].

6. PCBs life cycle overview

According to Andrae [29], Ravi [33], Canal Marques [4], and Deng [34] a number of methods and tools are related to environmental assessment, such as life cycle assessment (LCA), consequential life cycle analysis (CLCA), and ecological carbon footprint, all of which are intended to indicate which alternative is better than others. The life cycle of PCBs consists of four phases: the design and structuring, the board production and assembly, followed by the use phase, and, finally, recovery, recycling and disposal. Some phases are concerned in this paper.

6.1. PCB material and component

The PCBs legislations have confirmed that lead-based solder is a material with the greatest polluting potential, and it had to be banned to prevent its uncontrolled emissions. However, a full LCA would be necessary to discover the environmental behavior of the new materials that would replace it. Andrae [29] mentioned that, depending on the substitute solders, the demand for lead will decrease and for bismuth, copper, zinc, silver, antimony, and especially tin will increase. Furthermore, some studies reported the use of adhesives instead of lead-based solders. Electrically conductive adhesives (ECAs) consist of a polymeric binder matrix (about 50 % by volume or 20 % by weight), which is usually a bisphenol-A epoxy resin, and metal fillers in which the metal is usually Ag, Au, Cu, or Ni [4]. It is also possible to find metal spheres coated in polymer in the polymeric matrix [29]. Li and Wong [35] suggest that the adhesive ECA is generally more environmental-friendly than lead-based solders, flux cleaning is eliminated, and less overall processing steps are required.

In a comparative LCA study [34], it is proved that the biobased Material and natural fiber alternatives show a clear impact reduction compared to epoxy resins and glass fibers. Biopolymer named lignin was incorporated into traditional composite (glass fiber reinforced epoxy resin) as PCB substrate [36]. In a fully biobased materials study epoxidized linseed oil (ELO) and flax fibers were used to replace epoxy resin and glass fiber respectively. The results from this study show that substrate from flax fiber/ELO plus MPP meets most requirement standard categories in IPC- 4101A/20 [37]. Biopolymers, polyhydroxybutyrate (PHB), cellulose acetate (CA) and two different copolymers of polylactid acid and thermoplastic polyester elastomer (PLA+TPC) examined to be a used for flexible printed circuit boards [49].

6.2. PCBs design and structure

The design for environment, miniaturization, and less energy material usage result a sustainable product. Siddhaye and Sheng [38] analyzed the PCB assembly manufacturing and proposed a series of parametric models. Based on these models, they studied the link between waste emissions and energy consumption during the manufacturing process with parameters in product design. However, this study does not drive an optimal design solution for a sustainable PCB. However, the authors in the next study reveal the relationship between environmental impact and design parameters in PCB manufacturing [39]. Furthermore on design optimization, miniaturization is a fast growing alternative in the area of electronics manufacturing. Three dimensional molded interconnect devices (3D-MID) are 3D shaped thermoplastic substrates, carrying interconnecting conducting patterns and electronic components. Due to the combination of mechanical and electronic functions, they bear a vast number of benefits compared to conventional PCBs, like a high integration of different functions, a reduced number of parts and a great design flexibility which results great sustainability benefits [40].

6.3. PCBs manufacturing assembly

In the first assembly step, the screen printing process is essentially a simple and efficient method of reproducing patterns on a variety of substrates. This step has three primary waste flows; residue solder paste on the stencil that is cleaned at the end of the batch run or the end of a shift, solder that becomes clogged in the stencil apertures; and the solvents and water used to clean the stencil. The paste waste is in the form of airborne particulates, paste contamination on cleaning wipes, and solder and solvent contaminated water [19]. There are some studies to optimize the paste application using alternative environmental-friendly materials, resins, and bio-inks [41]. In the second assembly step, the electrical components automatically will be placed on the substrate.

However the machine uses considerable pneumatic and electrical energy, but the product defect due to the component mounting deviation is the main source waste in this step. A clean pick up nuzzle, precise feeder, and high resolution vision system for the machine is a good way to compensate the deviations in the process. The final assembly step is quit energy intensive where the solder paste should be sold on the substrate with high thermal energy. The waste outputs from soldering oven are thermal and mechanical energy, dross, flux, nitrogen and VOC emissions (Fig. 1). Assembled PCB units are then sent for testing (Automated Optical (AOI) inspection, X-Ray (AXI) inspection, etc.) and packaging, before dispatch.

6.4. PCBs recycling

As reported, studies have been carried out on methods that are used to recycle PCBs. In the vast majority, only a portion is recycled, mainly in order to recover valuable metals including copper because of considerable economic values [4]. Recycling process for waste PCB includes three process which is pretreatment, physical recycling, and chemical recycling. The pre-treatment stage includes disassembly of the reusable and toxic parts using shredding/separation [42, 43]. In the physical process several mechanical methods are used, including the separation by shape by using templates, magnetic separation, and separation based on electrical conductivity, separation based on density, and electrostatic separation by the corona method [4]. The chemical process or metallurgical processing includes pyrolysis, gasification, and depolymerization using supercritical fluids and hydrogenolic degradation to dissolve or melt the metal parts [44].

7. Trending green innovations

Molded interconnect devices (MID) are realized as miniaturized printed circuit with a great design flexibility and environmental benefits [40]. In printable electronics, conductive inks and dielectric inks are used when substituting traditional PCB with inkjet-printed interconnections. Using printing technology, several process steps involving considerable material consumption, such as etching and cleaning, are substituted with a single process consisting of adding material to the substrate [45]. Market analysis and research reports estimate that printed and organic electronics will become a huge, several hundred billion dollar business in the near future [46]. The company Würth Elektronik GmbH has been studying techniques to produce printed circuit boards that can have their materials separated and recycled after the end of their life cycle [47].

In an alternative process for green innovation, the electronic components and metal content can be easily separated out from the organic content at end-of-life. No separate printed circuit board is used to interconnect the components, so the process may be termed as "substrate-less". The basis of the method is assembly of electronic components onto a carrier which is subsequently over-moulded with a thermoplastic which could be biodegradable or soluble. Production of the interconnection pattern is the final step in the process [48]. The Reactive Nano Technologies (RNT) Company introduced an innovative approach to do the soldering process using low energy consumption. In this approach a layer of nano-films is placed in between of electronic component and solder paste. The film under the pressure or using laser will be activated. This activation produces sufficient thermal energy to do the soldering process on the board.

8. Summary and conclusion

This article presents an overview on sustainability issues with Lean paradigm perspective in PCB assembly and the alternative solutions for the recent green innovations and production of PCBs.

The main effort in the assembly production planning stage is how to smooth the process and transit from the batch process production to a continuous process using lean methods such as Just-in-Time (JIT), Kanban, Single Minute Exchange of Die (SMED), Value Stream Mapping (VSM), and etc. methods which obtain work in process (WIP) inventory and waste reduction. These methods also yield sustainability results, however it is not proved that to use them as sustainability tools.

Analysis of PCB assembly process for resource consumption recently becomes more important. The material element and PCBs components have been vastly discussed, but the energy element that is used in the assembly process is still in question. The PCB material structure has an increasing popularity among researchers. The PCBs compound result the sustainability degree of recycled material. Concerns on legislations, especially the joining components and solder alloy restrictions result the recent grow on bio-materials and natural resins usage, however recycling methods for these materials are not clear yet. Also, the design for environment and miniaturization structuring techniques provide resource consumption benefits and these are fast developing topics in the recent market. The material legislations and recycling difficulties also forces the research market for alternatives to the traditional process. Some methods have been reviewed earlier; however they have not been vastly accepted in the market due to the difficulties of reliabilities, technology transfer, and economics. Although these methods and innovations are more environmental-friendly, but still they are not solving the problem of mechanical recycling.

Acknowledgements

The authors would like to express their sincere thanks to the Free State of Bavaria for funding the project “Green Factory Bavaria” in the framework of the future initiative “Aufbruch Bayern”.

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